Diffuse Galactic Emission from Spinning Dust Grains

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ABSTRACT

Spinning interstellar dust grains produce detectable rotational emission in the 10-100 GHz frequency range. We calculate the emission spectrum, and show that this emission can account for the "anomalous" Galactic background component which correlates with $100\,\mu$m thermal emission from dust. Implications for cosmic background studies are discussed.

Subject headings: cosmic microwave background — dust, extinction — molecular processes — radiation mechanisms: thermal — radio continuum: ISM

1. Introduction

Experiments to map the cosmic background radiation (CBR) have stimulated renewed interest in diffuse Galactic emission. Sensitive observations of variations in the microwave sky brightness have revealed a component of the 14-90 GHz microwave continuum which is correlated with $100\,\mu$m thermal emission from interstellar dust (Kogut et al. 1996; de Oliveira-Costa et al. 1997; Leitch et al. 1997). The origin of this "anomalous" emission has been of great interest. While the observed frequency-dependence appears consistent with free-free emission (Kogut et al. 1996; Leitch et al. 1997), it is difficult to reconcile the observed intensities with free-free emission from interstellar gas (see §6 below).

A recent investigation of the rotational dynamics of very small interstellar grains (Draine & Lazarian 1998; hereinafter DL98) leads us instead to propose that this 10-100 GHz "anomalous" component of the diffuse Galactic background is produced by electric dipole rotational emission from very small dust grains under normal interstellar conditions.

Below we describe briefly our assumptions concerning the interstellar grain properties (§2), the dynamics governing the rotation of small grains (§3), the predicted emission spectrum and intensity (§4) and how it compares with observations (§5), and why the observed emission cannot be attributed to free-free (§6). In §7 we discuss implications for future CBR studies.

2. Grain Properties

The observed emission from interstellar diffuse clouds at 12 and 25 μm (Boulanger & Pérault 1988) is believed to be thermal emission from grains which are small enough that absorption of a single photon can raise the grain temperature to ~ 150 K for the 25 μm emission, and ~ 300 K for the 12 μm emission. Such grains contain $\sim 10^2 - 10^3$ atoms, and must be sufficiently numerous to account for ~20% of the total rate of absorption of energy from starlight.[1] A substantial fraction of these very small grains may be hydrocarbon molecules, as indicated by emission bands at 6.2, 7.7, 8.6, and 11.3 μm observed from diffuse clouds by *IRTS* (Onaka et al. 1996) and *ISO* (Mattila et al. 1996).

If the grains are primarily carbonaceous, they must contain $\sim 3 - 10\%$ of the carbon in the interstellar medium [in the model of Désert et al. (1990), polycyclic aromatic hydrocarbon molecules contain ~9% of the carbon]. The size distribution is uncertain. As in DL98, for our standard model "A" we assume a grain size distribution consisting of a power law $dn/da \propto a^{-3.5}$ (Mathis, Rumpl, & Nordsieck 1977; Draine & Lee 1984) plus a log-normal distribution containing 5% of the carbon; 50% of the mass in the log-normal distribution (i.e., 2.5% of the C atoms) is in grains with $N < 160$ atoms. The grains are assumed to be disk-shaped for $N < 120$, and spherical for $N > 120$.

The microwave emission from a spinning grain depends on the component of the electric dipole moment perpendicular to the angular velocity. Following DL98, we assume that a neutral grain has a dipole moment $\mu = N^{1/2}\beta$, where N is the number of atoms in the grain. Recognizing that there will be a range of dipole moments for grains of a given N, we assume that 25% of the grains have $\beta = 0.5\beta_0$, 50% have $\beta = \beta_0$, and 25% have $\beta = 2\beta_0$. For our standard models we will take $\beta_0 = 0.4$ debye, but since β is uncertain we will examine the effects of varying β_0.

If the grain has a charge Ze, then it acquires an additional electric dipole component arising from the fact that the centroid of the grain charge will in general be displaced from the center of mass (Purcell 1979); we follow DL98 in assuming a characteristic displacement of $0.1a_x$, where a_x is the rms distance of the grain surface from the center of mass, and in computing the grain charge distribution $f(Z)$ including collisional charging and photoelectric emission.

Finally we assume that the dipole moment is, on average, uncorrelated with the spin

[1] Assuming a Debye temperature $\Theta = 420$ K, a 6 eV photon can heat a particle with N=277 atoms to $T = 200$ K.

axis, so that the mean-square dipole moment transverse to the spin axis is

$$\mu_\perp^2 = (2/3)\left(\beta^2 N + 0.01 Z^2 e^2 a_x^2\right) \quad . \tag{1}$$

We will show results for 6 different grain models. Models B and C differ from our preferred model A by having β_0 decreased or increased by a factor 2. Model D differs by having twice as many small grains in the log-normal component. In model E even the smallest grains are spherical, whereas in model F the smallest grains are assumed to be linear.

3. Rotation of Interstellar Grains

Rotation of small interstellar grains has been discussed previously, including the fact that the rate of rotation of very small grains would be limited by electric dipole emission (Draine & Salpeter 1979). Ferrara & Dettmar (1994) recently estimated the rotational emission from very small grains, noting that it could be observable up to ∼100 GHz, but they did not self-consistently evaluate the emission spectrum including the effects of radiative damping. A number of distinct physical processes act to excite and damp rotation of interstellar grains, including collisions with neutral atoms, collisions with ions and long-range interactions with passing ions (Anderson & Watson 1993), rotational emission of electric dipole radiation, emission of infrared radiation, formation of H_2 molecules on the grain surface, and photoelectric emission. We use the rates for these processes summarized in DL98; the results reported here assume that H_2 does *not* form on small grains, so that there is no contribution by H_2 formation to the rotation. As discussed in DL98, observed rates of H_2 formation on grains limit the H_2 formation torques so that they can make at most a minor contribution to the rotation of the very small grains of interest here.

Emission in the 10-100 GHz region is dominated by grains containing $N \lesssim 10^3$ atoms. For these very small grains under CNM conditions (see Table 2), rotational excitation is dominated by direct collisions with ions and “plasma drag”. The very smallest grains ($N \lesssim 150$) have their rotation damped primarily by electric dipole emission; for $150 \lesssim N \lesssim 10^3$ plasma drag dominates.

4. Predicted Emission

Following DL98, we solve for the rms rotation rate $\langle\nu^2\rangle^{1/2}$, which depends on the local environmental conditions (density $n_{\rm H}$, gas temperature T, fractional ionization $n_e/n_{\rm H}$, and

the intensity of the starlight background), the grain size, and the assumed value of β in eq.(1). Then, assuming a Maxwellian distribution of angular velocities for each grain size and β, we integrate over the size distribution to obtain the emission spectrum for the grain population.

Interstellar gas is found in a number of characteristic physical states (see, e.g., McKee 1990). By mass, most of the gas and dust is found in the "Warm Ionized Medium" (WIM), "Warm Neutral Medium" (WNM), "Cold Neutral Medium" (CNM), or in molecular clouds (MC). In the diffuse regions (WIM,WNM,CNM) the bulk of the dust is heated by the general starlight background to temperatures $\sim 18\,\mathrm{K}$ where it radiates strongly at $\sim 100\,\mu\mathrm{m}$ – thus the $100\,\mu\mathrm{m}$ emission traces the mass of the WIM, WNM, and CNM material. Relatively little molecular material is present at $|b| > 30\,\mathrm{deg}$ where sensitive CBR observations are directed. Hence we consider only the WIM, WNM, and CNM phases in the present discussion.

In Table 1 we list the assumed properties for each of the interstellar medium components which we consider here. For $b > 30°$, 21 cm observations (Heiles 1976) indicate $N_{\mathrm{H}}(\mathrm{WNM}) + N_{\mathrm{H}}(\mathrm{CNM}) \approx 3.4 \times 10^{20}(\csc b - 0.2)\,\mathrm{cm}^{-2}$, divided approximately equally between WNM and CNM phases (Dickey, Salpeter, & Terzian 1978). Dispersion measures toward pulsars in 4 globular clusters (Reynolds 1991) indicate an ionized component $N_{\mathrm{H}}(\mathrm{WIM}) \approx 5 \times 10^{19} \csc b\,\mathrm{cm}^{-2}$, after attributing $\sim$20% of the electrons to hot ionized gas (McKee 1990). In Figure 1 we show the predicted rotational emissivity per H nucleon, where we have taken the weighted average of emission from CNM, WNM, and WIM, according to the mass fractions in Table 2. The heavy curve is for our preferred grain model A; the results shown for grain models B-F serve to illustrate the uncertainty in the predicted emission. All models have the grain emissivity peaking at about $\sim$30 GHz; when the smallest grains are taken to be spheres (model E), the emission peak shifts to $\sim$35 GHz because of the reduced moment of inertia of these smallest grains.

In addition to the rotational emission from the very small grains, we expect continuum emission from the vibrational modes of the larger dust grains, which are thermally excited according to the grain vibrational temperature T_d. The vibrational emission per H atom is assumed to vary as $j_\nu/n_{\mathrm{H}} = A\nu^\alpha B_\nu(T_d)$. We show the emissivity for $\alpha = 1.5$, 1.7, and 2; in each case we adjust A and T_d so that νj_ν peaks at $\lambda = 140\,\mu\mathrm{m}$, with a peak emissivity $4\pi\nu j_\nu/n_{\mathrm{H}} = 3 \times 10^{-24}\,\mathrm{ergs\,s^{-1}H^{-1}}$ (Wright et al. 1991; cf. Fig. 5 of Draine 1995). The resulting values of α and T_d are within the range found by Reach et al. (1995). We will use $\alpha = 1.7$ to estimate the thermal emissivity; by comparison with the estimates for $\alpha = 1.5$ and $\alpha = 2$ we see that the thermal emission at $\sim$100 GHz is uncertain by at least a factor ~ 2. We expect the thermal emission to dominate for $\nu \gtrsim 70$ GHz, with the rotational

emission dominant at lower frequencies.

5. Comparison With Observations

Figure 2 shows the emission per H nucleon for our preferred parameters (model A, $\alpha = 1.7$), for each phase as well as the weighted average over the three phases. Also shown are the observational results of Kogut et al. (1996) (based on cross-correlation of *COBE* DMR 31.5, 53, and 90 GHz maps with *COBE* DIRBE 100 μm maps); de Oliveira-Costa et al. (1997) (based on cross-correlation of Saskatoon 30 and 40 GHz maps with *COBE* DIRBE 100 μm maps; and Leitch et al. (1997) (based on cross-correlation of Owens Valley mapping at 14.5 and 32 GHz with *IRAS* 100 μm maps. All three papers reported strong positive correlations of microwave emission with 100 μm thermal emission from dust. The observed correlation of 100 μm emission with 21cm emission, $I_\nu(100\,\mu\mathrm{m}) \approx 0.85\mathrm{MJy\,sr^{-1}}(N_{\mathrm{H}}/10^{20}\,\mathrm{cm^{-2}})$ (Boulanger and Pérault 1988), allows us to infer the excess microwave emission per H atom, as shown in Fig. 2.

While Kogut et al. attribute only $\sim$50% of the 90 GHz signal to thermal emission, we estimate that the 90 GHz signal is predominantly vibrational emission from dust. The rotational emission which we predict appears to be in good agreement with the 30-50 GHz measurements by Kogut et al., de Oliveira-Costa et al., and Leitch et al. We conclude that rotational emission from small dust grains accounts for a substantial fraction of the "anomalous" Galactic emission at 30-50 GHz.

Leitch et al. also report excess emission at 14.5 GHz which is correlated with 100 μm emission from dust. For our model A, rotational emission from dust grains accounts for only $\sim$30% of the reported excess emission at 14.5 GHz. Additional emission at 14.5 GHz could be obtained by changes in our adopted parameters: model B, in which dipole moments are increased by a factor of two, would be in good agreement with the 14.5 GHz result of Leitch et al. However, the assumed dipole moment is larger than we consider likely, so we do not favor this model. We could of course also improve agreement by increasing the number of small grains in the size range ($N \approx 100$) primarily radiating near 14.5 GHz.

We note that there may be systematic variations in the small grain population from one region to another. The signal reported by Leitch et al. at 30 GHz is about a factor of $\sim$3 larger than the results of Kogut et al. and de Oliveira-Costa et al., both of which average over much larger areas than the observations of Leitch et al. Additional observations to measure more precisely the Galactic emission will be of great value. We also note that although Leitch et al. found no correlation of 14.5 GHz excess with synchrotron maps

at 408 MHz, synchrotron emission and rotational emission from dust are expected to contribute approximately equally to the diffuse background near 14 GHz (see Fig. 3). We conjecture that some of the 100 μm-correlated 14.5 GHz radiation observed by Leitch et al. may be synchrotron emission which is enhanced by increased magnetic field strengths near concentrations of gas and dust.

6. Why Not Free-Free?

Based on the observed frequency-dependence of the excess radiation, Kogut et al. proposed that it was a combination of thermal emission from dust plus free-free emission from ionized hydrogen. Leitch et al. reached the same conclusion based on their 14.5 and 32 GHz measurements.

Leitch et al. noted that if the proposed spatially-varying free-free emission originated in gas with $T \lesssim 10^4\,\mathrm{K}$, it would be accompanied by Hα emission at least 60 times stronger than the observed variations in the Hα sky brightness (Gaustad et al. 1996) on the same angular scales. Noting that the ratio of Hα to free-free radio continuum drops as the gas temperature is increased above $\sim 3 \times 10^4\,\mathrm{K}$, Leitch et al. proposed that the "anomalous" emission originated in gas at $T \gtrsim 10^6\,\mathrm{K}$,

However, this proposal appears to be untenable. According to Leitch et al., the observed emission excess would require an emission measure $EM \approx 130 T_6^{0.4}\,\mathrm{cm^{-6}\,pc}$ with $T_6 \equiv (T/10^6\,\mathrm{K}) \gtrsim 1$ near the North Celestial Pole (NCP, $l \approx 123°$, $b \approx 27.4°$). Kogut et al. and de Oliveira-Costa et al. reported a weaker signal at 30 GHz, corresponding to an emission measure $\sim 40 T_6^{0.4}\,\mathrm{cm^{-6}\,pc}$ toward the NCP. The DMR observations (Kogut et al. 1996) cover a substantial fraction of the sky, and would imply an emission measure normal to the galactic disk $\sim 2 \sin 27° \times 40 T_6^{0.4}\,\mathrm{cm^{-6}\,pc}$. For $T \gtrsim 10^6\,\mathrm{K}$ the radiative cooling rate can be approximated by $\sim 1 \times 10^{-22} (T_6^{-1} + 0.3 T_6^{1/2}) n_{\mathrm{H}} n_e\,\mathrm{ergs\,cm^3\,s^{-1}}$ (cf. Bohringer & Hensler 1989) so the power radiated per disk area would be $\sim 30 (T_6^{-0.6} + 0.3 T_6^{0.9}) L_\odot\,\mathrm{pc^{-2}}$, far in excess of the $0.3 L_\odot\,\mathrm{pc^{-2}}$ energy input for one 10^{51} ergs supernova per 100 yr per 10 kpc radius disk. Evidently the proposed attribution of the "anomalous emission" to bremsstrahlung from hot gas can be rejected on energetic grounds.

7. Discussion

Very small dust grains have been invoked previously to explain the observed 3 - 60 μm emission from interstellar dust (Leger & Puget 1984; Draine & Anderson 1985; Désert,

Boulanger, & Puget 1990). We have calculated the spectrum of rotational emission expected from such dust grains, and shown that it should be detectable in the 10 – 100 GHz region. In fact, we argue that this emission has already been detected by Kogut et al. (1996), de Oliveira-Costa et al. (1997), and Leitch et al. (1997).

Rotational emission from very small grains and “thermal” (i.e., vibrational) emission by larger dust grains is an important foreground which will have to be subtracted in future sensitive experiments to measure angular structure in the CBR. To illustrate the relative importance of the emission from dust, in Fig. 3 we show the estimated rms variations in Galactic emission near the NCP ($l = 123°$, $b = 27.4°$), representative of intermediate galactic latitudes. The HI column density is taken to be $N(\mathrm{H}^0) = 6.05 \times 10^{20}\,\mathrm{cm}^{-2}$ (Hartmann & Burton 1997), plus an additional column density $N(\mathrm{H}^+) \sim 1.3 \times 10^{20}\,\mathrm{cm}^{-2}$ of WIM. We take 20% as an estimate of the rms variations in column density on angular scales of a few degrees.

We also show the synchrotron background near the NCP, based on a total antenna temperature of 3.55 K at 1.42 GHz (Reich 1982) and $I_\nu \propto \nu^{-1}$ at higher frequencies. The synchrotron background is smoother than the HI; we take 5% as an estimate of the rms synchrotron variations on angular scales of a few degrees. From the standpoint of minimizing confusion with non-CBR backgrounds, 70-100 GHz appears to be the optimal frequency window.

The “thermal” emission originates in larger grains, which are known to be partially aligned with their long axes perpendicular to the local magnetic field; above 100 GHz most of the emission is thermal, and we estimate that this will be $\sim 5\%$ linearly polarized perpendicular to the magnetic field (Dotson 1996 has observed up to 7% polarization at $100\,\mu$m toward M17). Below $\sim$50 GHz most of the emission is rotational. At this time it is not clear whether the angular momentum vectors of very small dust grains will be aligned with the galactic magnetic field. Ultraviolet observations of interstellar polarization place limits on such alignment (Kim & Martin 1995) but do not require it to be zero. If the grain angular momenta tend to be aligned with the galactic magnetic field, then the rotational emission will tend to be polarized perpendicular to the magnetic field. Physical processes which could produce alignment of these small grains will be discussed in future work (Lazarian & Draine 1998). Even modest ($\sim$1%) polarization of the dust emission could interfere with efforts to measure the small polarization of the CBR introduced by cosmological density fluctuations.

According to our model, the ~ 30 GHz emission and diffuse $12\,\mu$m emission should be correlated, as both originate in grains containing $\sim 10^2$ atoms; future satellite observations of the diffuse background can test this. Future observations by both ground-based

experiments and satellites such as *MAP* and *PLANCK* will be able to characterize more precisely the intensity and spectrum of emission from interstellar dust grains in the 10-200 GHz region. Measurements of the 10-100 GHz emission will constrain the abundance of very small grains, including spatial variations, as well as their possible alignment.

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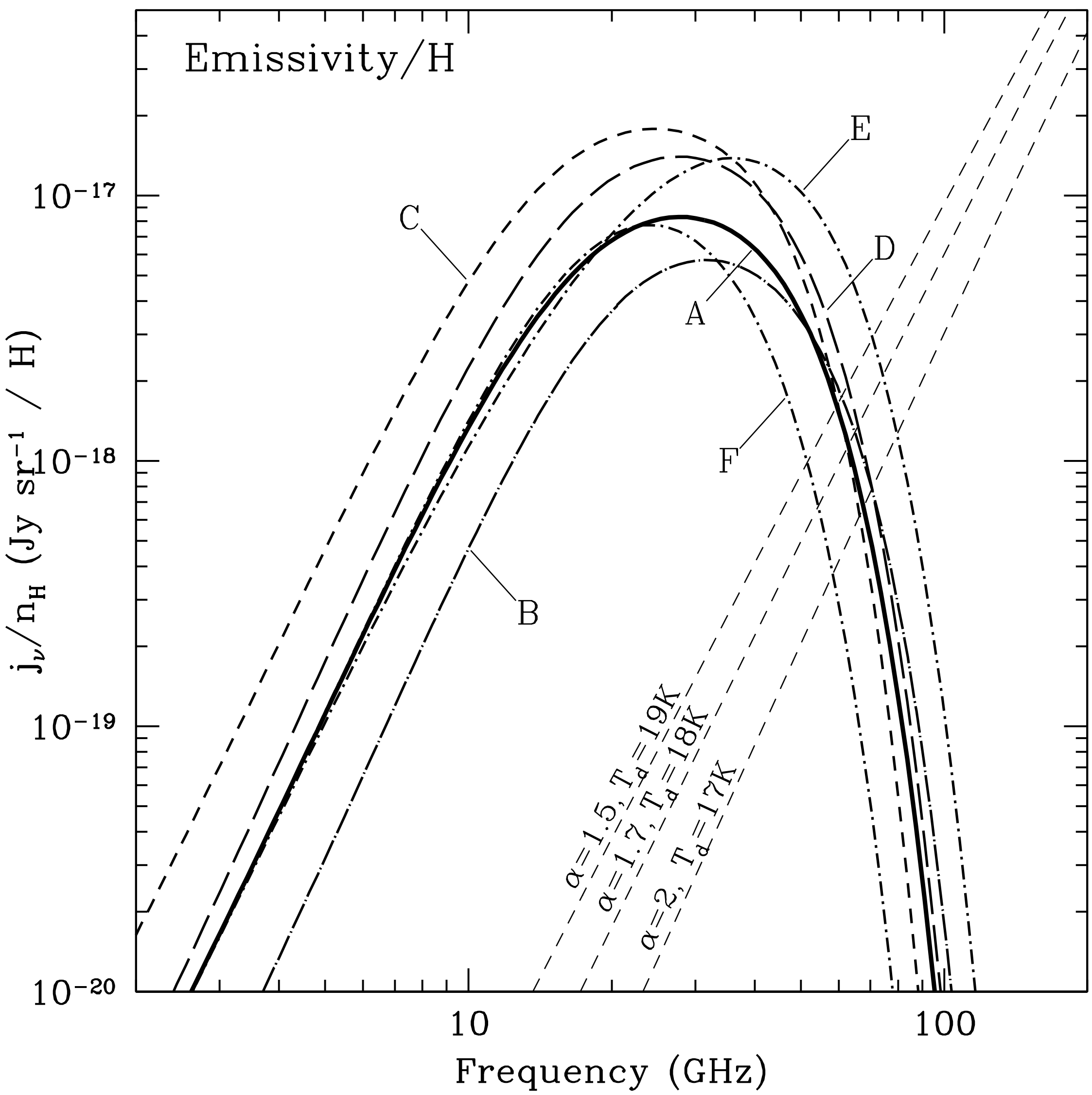

Fig. 1.— Predicted rotational emissivity/H of interstellar dust at $|b| \gtrsim 20°$. We assume the mix of cloud properties given in Table 2. Curves are labelled by grain model, A-F (see Table 1). A is the preferred grain model. Estimates for the vibrational ("thermal") emission from $a \gtrsim 0.01\,\mu$m grains are labelled by α and T_d (see text).

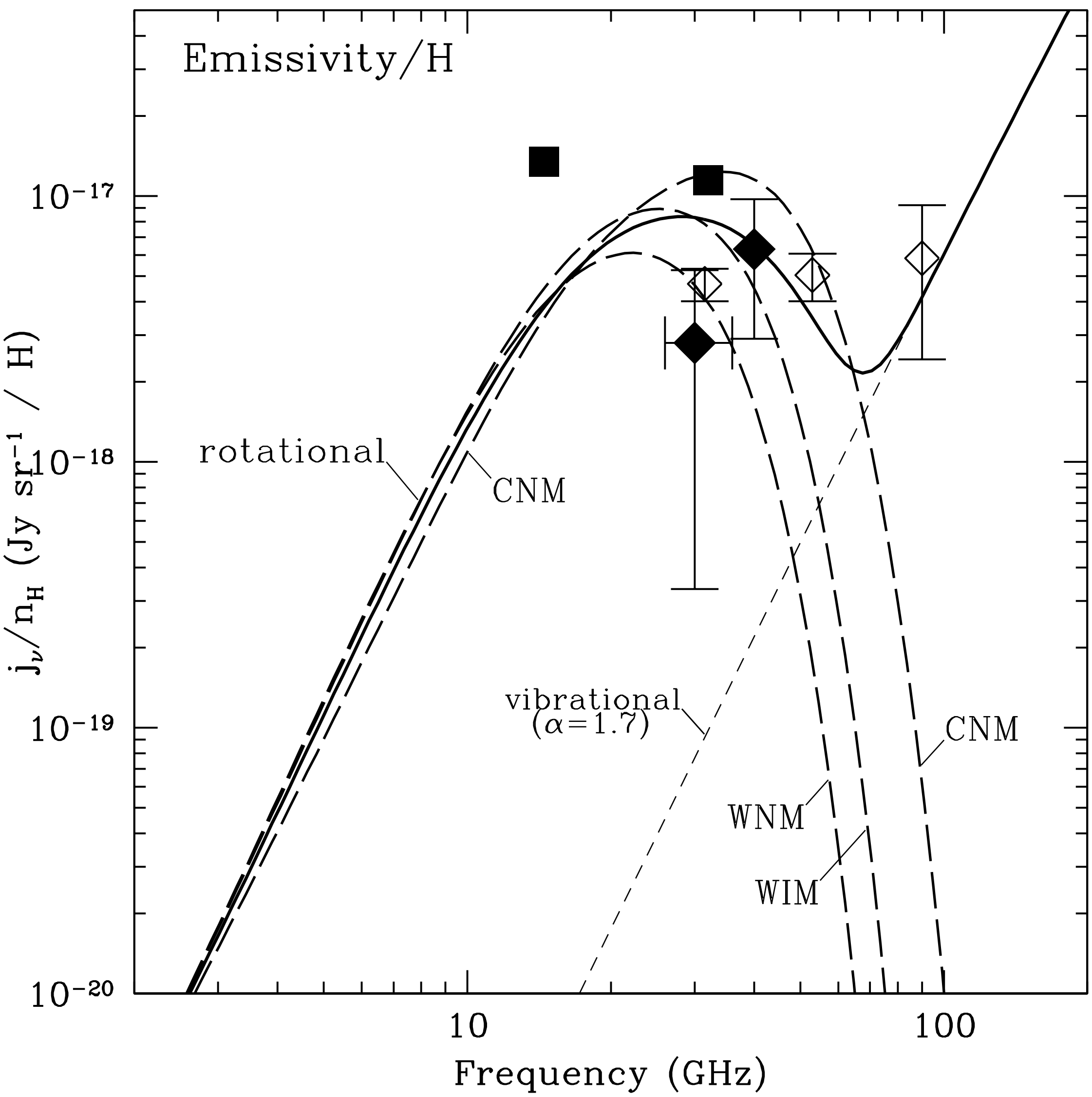

Fig. 2.— Solid line is the predicted emissivity/H of the interstellar medium at $|b| \gtrsim 20°$ for the preferred grain model ("A"), averaged over CNM, WNM, and WIM phases of interstellar gas. The vibrational and rotational components of this emission are shown as broken lines. Also shown are the emissivity per H atom for each of these phases. Symbols show observational results from *COBE* DMR (open diamonds; Kogut et al. 1996); Saskatoon (filled diamonds; de Oliveira-Costa et al. 1997); and Owens Valley (filled squares; Leitch et al. 1997).

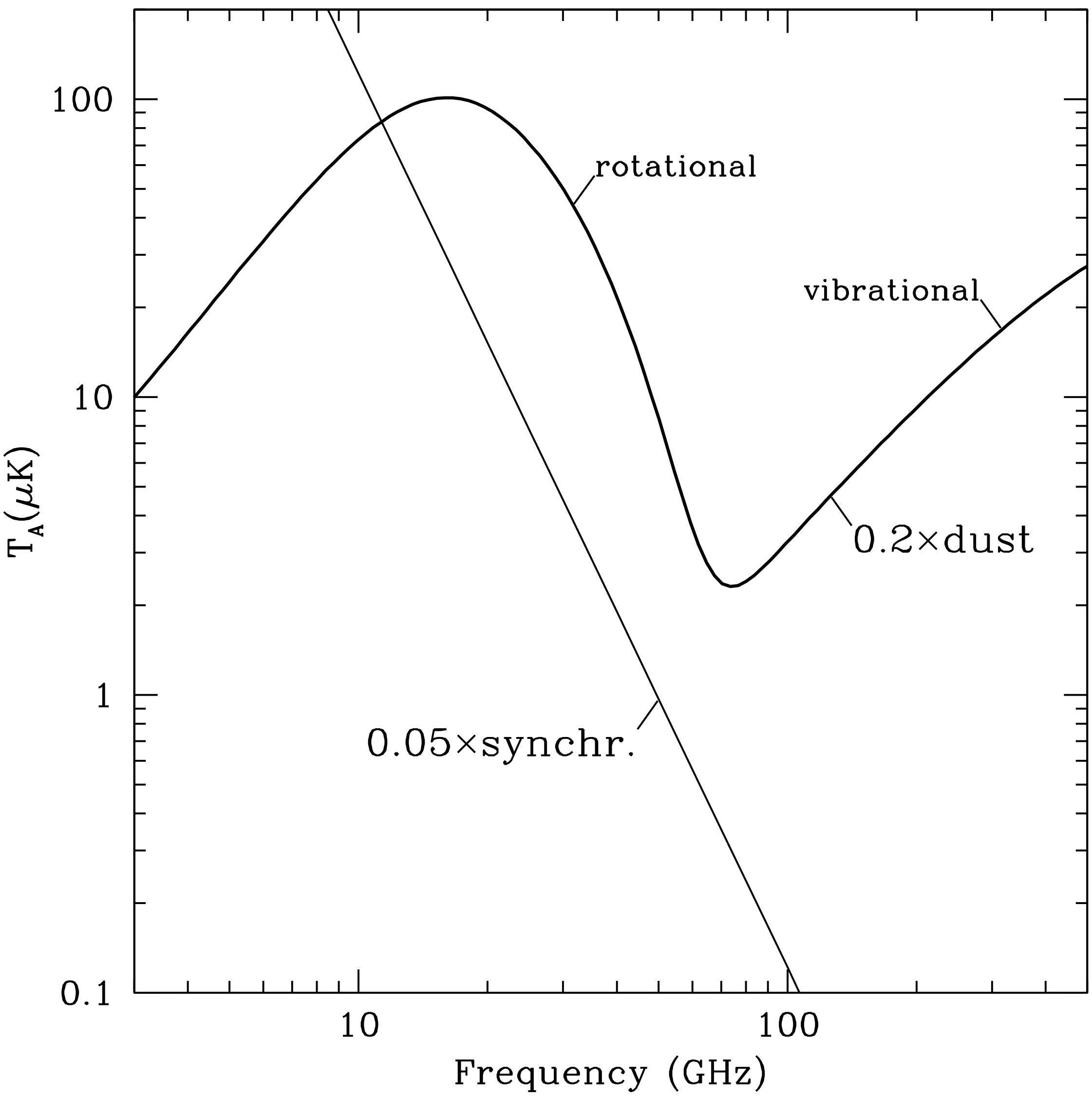

Fig. 3.— Estimated rms variations on scales of a few degrees from galactic foregrounds near the North Celestial Pole (see text); the dust column density is assumed to vary by ∼20%, and the synchrotron emission by ∼5%.

quantity	A	B	C	D	E	F
carbon fraction[a]	0.05	0.05	0.05	0.1	0.05	0.05
$35 < N < 120$ shape[b]	disk	disk	disk	disk	sphere	disk
$25 < N < 35$ shape[c]	disk	disk	disk	disk	sphere	linear
β_0 (debye)[d]	0.4	0.2	0.8	0.4	0.4	0.4

Table 1: Models for Very Small Grains

[a]Fraction of cosmic carbon abundance in log-normal component (see text).

[b]Shape of grains containing $35 < N < 120$ atoms (see text).

[c]Shape of grains containing $25 < N < 35$ atoms (see text).

[d](25,50,25)% of grains are taken to have $\beta = (0.5, 1, 2)\beta_0$ (see eq.1).

quantity	CNM	WNM	WIM
mass fraction[a]	0.43	0.43	0.14
$n_{\rm H}(\,{\rm cm}^{-3})$	30	0.4	0.1
$T(\,{\rm K})$	100.	6000.	8000.
χ	1.	1.	1.
$x_{\rm H} \equiv n({\rm H}^+)/n_{\rm H}$	0.0012	0.1	0.99
$x_M \equiv n(M^+)/n_{\rm H}$[b]	0.0003	0.0003	0.001

Table 2: Idealized phases for diffuse interstellar matter.

[a]Fraction of CNM+WNM+WIM in each phase (see text).

[b]Relative abundance of ions other than H^+ or He^+.